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Tsunami wave impact on walls & beaches

Jannette B. Frandsen http://lhe.ete.inrs.ca 27 Mar. 2014

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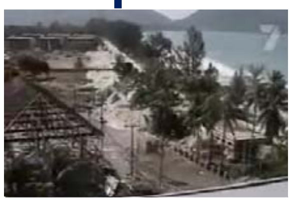
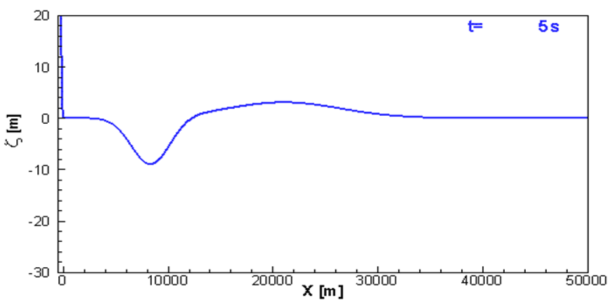
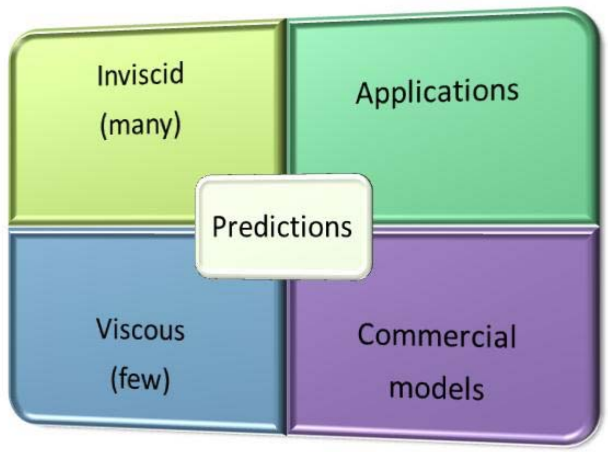
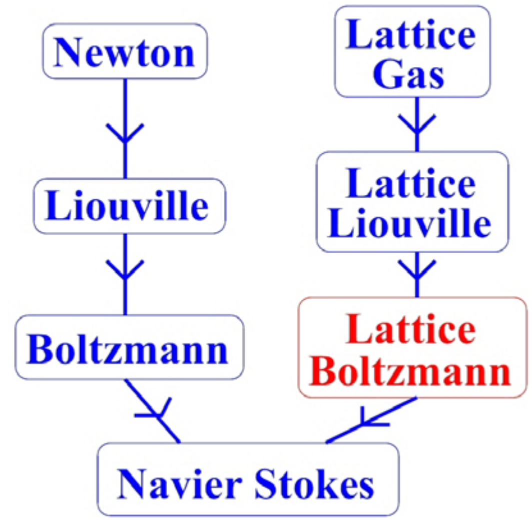
Tsunami wave impact on walls & beaches

- Numerical predictions









- Experiments
  - Small scale;
  - Large scale.

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Numerical Free-surface models

Inviscid models

- Airy, Stokes II
- Stokes III-V, stream function
- Fully nonlinear
- NLSW, Boussinesq
- 3rd generation spectral

Applications

- Large bodies: ships, FPU, fixed offshore platforms
- Offshore wind farms, tidal machines, WECs
- Oscillations: harbours/Lakes, sloshing, runup/overtopping
- MetOcean conditions & Resource assessment

Viscous models

- RANS VOF
- SPH + subgrid scale
- Lattice Boltzmann

Solvers

- Commercial: Flow3D, Xflow, WAMIT, ANSYS Aqwa, WAM, SWAN.
- Research: COULWAVE, FUNWAVE, SWAN, MIKE

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Motivation & fundamental questions

Traditional research models:

- **Numerical investigations of VIV & free surface water waves: continuum mechanics models.**

Alternative research models:

- **Bridge length/time scales btw. micro and continuum mechanics level.**

- **Identify numerical model approach aiming at:**
  1. **FSI/High *Re* problems;**
  2. **Fr > 1 problems;**
  3. **Nonlinear free surface water wave problems;**
  4. **Wave-seabed interactions;**
  5. **Water wave bluff body interactions?**

VIV = Vortex Induced Vibrations;
FSI = Fluid Structure Interaction.

Comparison of numerical methods

	FD σ-method	RANS VOF	LBM	SPH	PFEM
Grid dependent soln.	yes	yes	yes	no	yes
Wave continuous	yes	yes	yes	yes	yes
Nonlinear waves	yes	yes	yes	yes	yes
Free-surface algorithm	yes	yes	Yes/no	no	yes
Wave breaking	no	yes	Yes (?)	yes	yes
Bubble break-up	no	no	yes	no	no
Poisson freedom	yes	no	Yes (no)	yes	no
Viscosity	ok	ok	challenge	challenge	ok
BC simple	ok	no	yes	no	no
FSI/arbitrary geometry/topologies	no	yes	yes	yes	yes
Efficient parallelization	no	no	Yes/no	?	?
CPU efficiency	Ok/small domains	no	Ok so far	no	?
GPU efficiency	?	?	Ok so far	?	?

Kinetic modeling approach:

- Why….
- Breaking wave predictions,
- Local free-surface model and coupling effects.

L. Boltzmann

On the Analogy btw. Water waves and gas dynamics theory:

- ***"….knowledge and methods established in gas dynamics can be transferred directly to long water waves."*** **Mei**, "The applied dynamics of ocean surface waves", 1989;
- ***"…..impossible to doubt a close connection btw. mathematical analogy of gas dynamics and the structure underlying long surf on beaches"***. **Meyer**, Physics of Fluids, 1986;
- **Wehausen & Laitone**, "Surface Waves", 1960;
- **Stoker**, "Water Waves", 1957;
- **Courant & Friedrichs**, "Supersonic flow and shock waves", 1948.
- **Einstein, H. & Baird**, "…surface shock waves on liquids & shocks in compressible gases." CalTech Report, 1946.
- **Riabouchinsky**, 1932.

Non-breaking wave models – CPU based

- Salmon 1999. Journal of Marine Research 57, 503-535.
- Ghidaoui et al. 2001. Intl. J. for Num. Methods in Fluids 35.
- Buick & Greated 2003. Physics of Fluids 10 (6), 1490-1511.
- Zhou 2004. LB Methods for Shallow Water Flows. Springer.
- Zhong et al. 2005. Advances in Atmos. Sciences 22(3).
- Ghidaoui et al. 2006. J. Fluids Mechanics 548.
- Frandsen 2006. Intl. Journal of CFD 20 (6).
- Que & Xu 2006. Intl. J. Num. Meth. in Fluids 50.
- Thommes et al. 2007. Intl. J. Num. Meth. in Fluids.
- Frandsen 2008. Advanced Numerical Models for Simulating Tsunami Waves & Runup. Advances in Coastal & Ocean Engrg. World Scientific (10).
- ......
- Parmigiani, A., et al. 2013. Intl. J. Modern Physics C.

– CPU based

Breaking wave models

- Ginzburg, I. & Steiner, K. 2003. Lattice Boltzmann model for free-surface flow and its application to filling process in casting. *J. of Comp. Physics* **185**.
- Kraftczyk, M. & Tölke, J. 2004. Lattice-Boltzmann methods - basics and recent progress. *NAFEMS CFD Workshop on simulation of complex flows*, Germany.
- Körner, C., Thies, M. H., Thürey, N. & Rüde, U. 2005. Lattice Boltzmann model for free-surface flow for modeling foaming. *J. of Statistical Physics* **121** (1-2).
- Thürey, N. 2006. Physically based animation of free surface flows with the Lattice Boltzmann method. *PhD thesis.* Der Technischen Fakultät der Universität Erlangen-Nürnberg, Germany.

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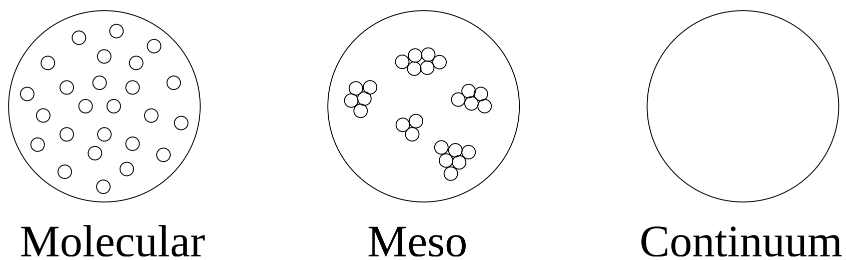
Observations

- Non-breaking wave model:
  1. NLSW equations;
  2. No free-surface algorithm.

- Breaking wave model:
  1. Navier-Stokes equations;
  2. Free-surface algorithm: Volume of Fluid method

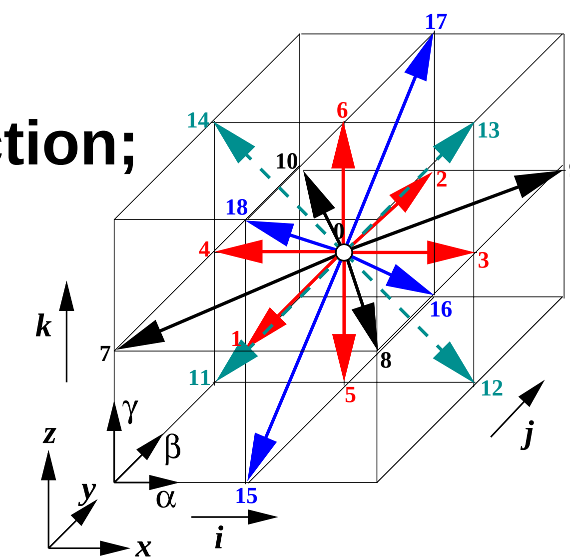
Lattice Boltzmann Model

- **Fluid motion governed by Navier-Stokes eqn.;**
- **Particles move along lattice in collision process;**
- **Collisions allow particles to reach local equilibrium;**



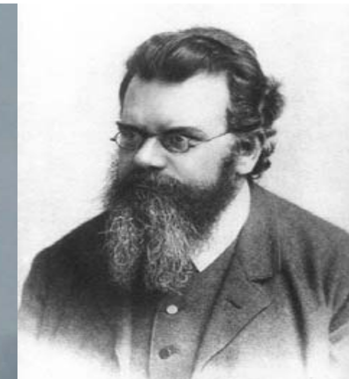
- **Discretized particle velocity distribution function;**
- **3D: ex. 19 or 27 velocities on a cubic lattice;**
- **Hydrodynamic fields:**

  total depth, velocity and pressure.

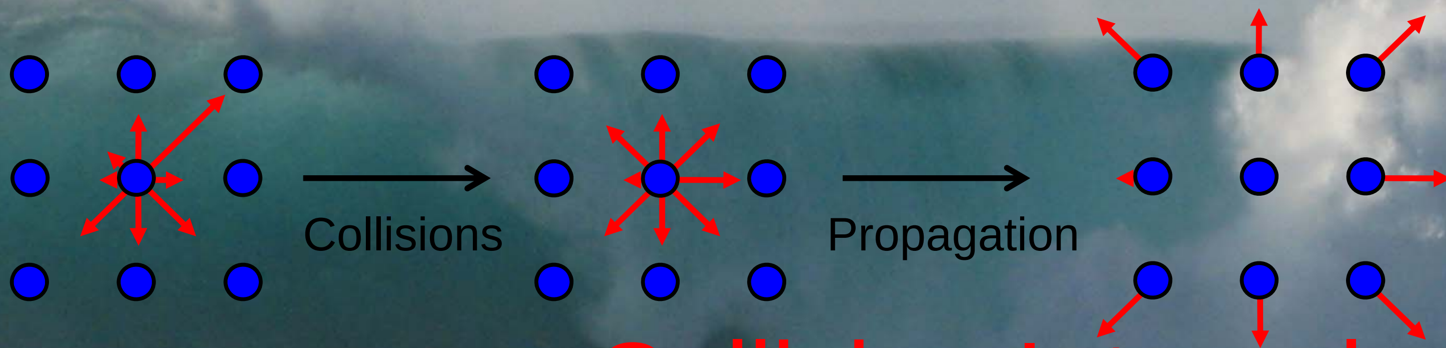


Original Boltzmann Equation

$$\frac{\partial f}{\partial t} + c_i \cdot \nabla f = \frac{1}{\epsilon} J(f, f) \, ,$$



L. Boltzmann



Collision Integral

$$J(f, f) = \frac{1}{2m} \int_0^{\pi} d\theta \int_0^{2\pi} d\epsilon \int dV \, B(\theta, V) \, (f_1' f_2' - f_1 f_2)$$

Approximations:

- **Single time relaxation,**
  - ***LBGK model*, after Bhatnagar et al. (1954) ;**
- **Multi Relaxation Times, MRT models.**

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Lattice Boltzmann Model in Shallow water

Single phase LBGK model (Bhatnagar et al., 1954; Salmon, 1999):

$$\frac{\partial f_i}{\partial t} + c_i \cdot \nabla f = \frac{f_i - f_i^{eq}}{\tau} + F \,,$$

where F denotes force term(s) and f_i^{eq} represents equilibrium distribution functions. Classic LB-stencil: $\tau = 0.5 + 3(\nu\,\Delta\,t)/\Delta\,x^2$.

Constraints: The moments represent conservation of mass and momentum and static/dynamic pressures, as follows

$$\sum_i f_i^{eq} = h(x,t)\ ; \qquad \sum_i c_i\, f_i^{eq} = h(x,t)\, u_i\ ;$$

$$\sum_i c_i\, c_j\, f_i^{eq} = \frac{1}{2}\, g\, h(x,t)^2\, \delta_{ij} + h(x,t)\, u_i\, u_j\ ,$$

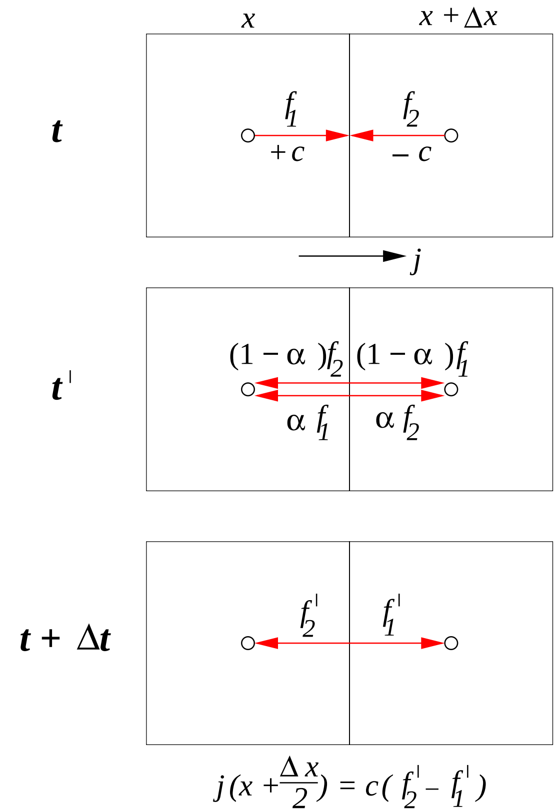
where $h = h_0 + \zeta$, h_0 is the initial still water depth and ζ is the free surface elevation. g is gravity due to acceleration, u denotes macroscopic velocities, and δ_{ij} is the kronecker delta.

LBGK model example

❑ Discrete velocity model (D1Q3)

$$f_{i=0}^{eq} = h_0 + \zeta - \frac{g(h_0+\zeta)^2 \Delta t^2}{2\Delta x^2} - \frac{(h_0+\zeta)\Delta t^2}{\Delta x^2}(u_i u_i)$$

$$f_{i=1,2}^{eq} = \frac{g(h_0+\zeta)^2 \Delta t^2}{4\Delta x^2} + \frac{(h_0+\zeta)\Delta t u_i}{2\Delta x} c_i + \frac{(h_0+\zeta)\Delta t^2}{2\Delta x^2}(u_i u_i)$$



❑ The macroscopic variables

$$\zeta = \sum_{i=0}^{2} f_i - h_0$$

$$u = \frac{1}{(h_0+\zeta)} \sum_{i=0}^{2} c_i f_i$$

(Soln.: 0. Initial conditions; 1. Calculate f^{eq}; 2. Compute f_i.)

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Long Wave Run-up Studies

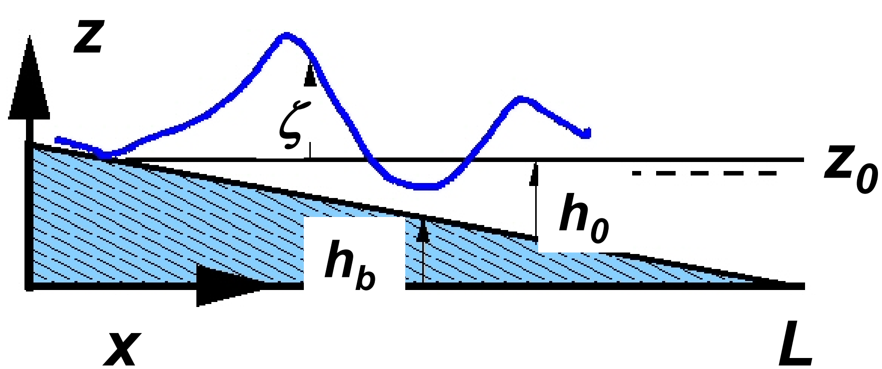
$$h_0/L_0 \longrightarrow 0\ ,\ \ \varepsilon = a/h_0 = O(1)$$

- **Free-surface: no algorithm is prescribed in non-overturning wave model;**
- **Wave run-up: dry/wet phase ($h \longrightarrow 0$):**
  - ❑ **Automatically handled (i.e., thin film: $h \sim 10^{-5}$m);**
  - ★ **Shoreline algorithm;**
  - ❑ **"Slot method".**
- **Problem Set-up**

L = 50 km

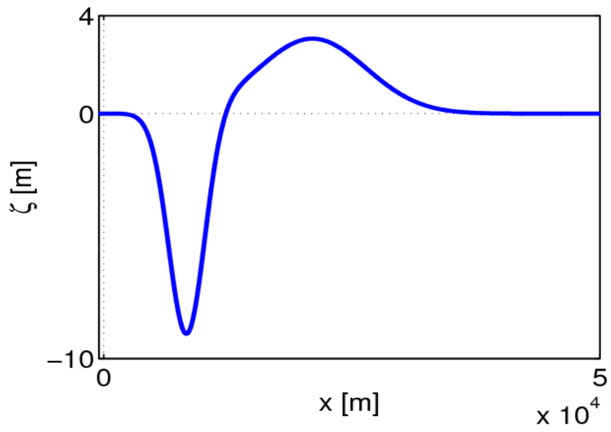
$Z_0 = 5000$ m

$\partial h_b/\partial x = 1/10$



Initial Conditions & Boundaries

Initially the velocity in the flow domain is zero and the free surfac
described by the form of a leading depression N-wave shape,
typically caused by an offshore submarine landslide,



$$\zeta = a_1\, e^{-k_1 (x-x_1)^2} - a_2\, e^{-k_2 (x-x_2)^2} \quad \text{and} \quad u = 0 \quad \text{at t=0}\,,$$

where $a_1 = \frac{1}{3} a_2$=0.006, a_2=0.018, $k_1 = \frac{1}{9} k_2$=0.4444, x_1=4.1209 and x_2=1.6384, after Carrier et al. (2003).

The computational domain: $x \in$ [-500, 50500] m.

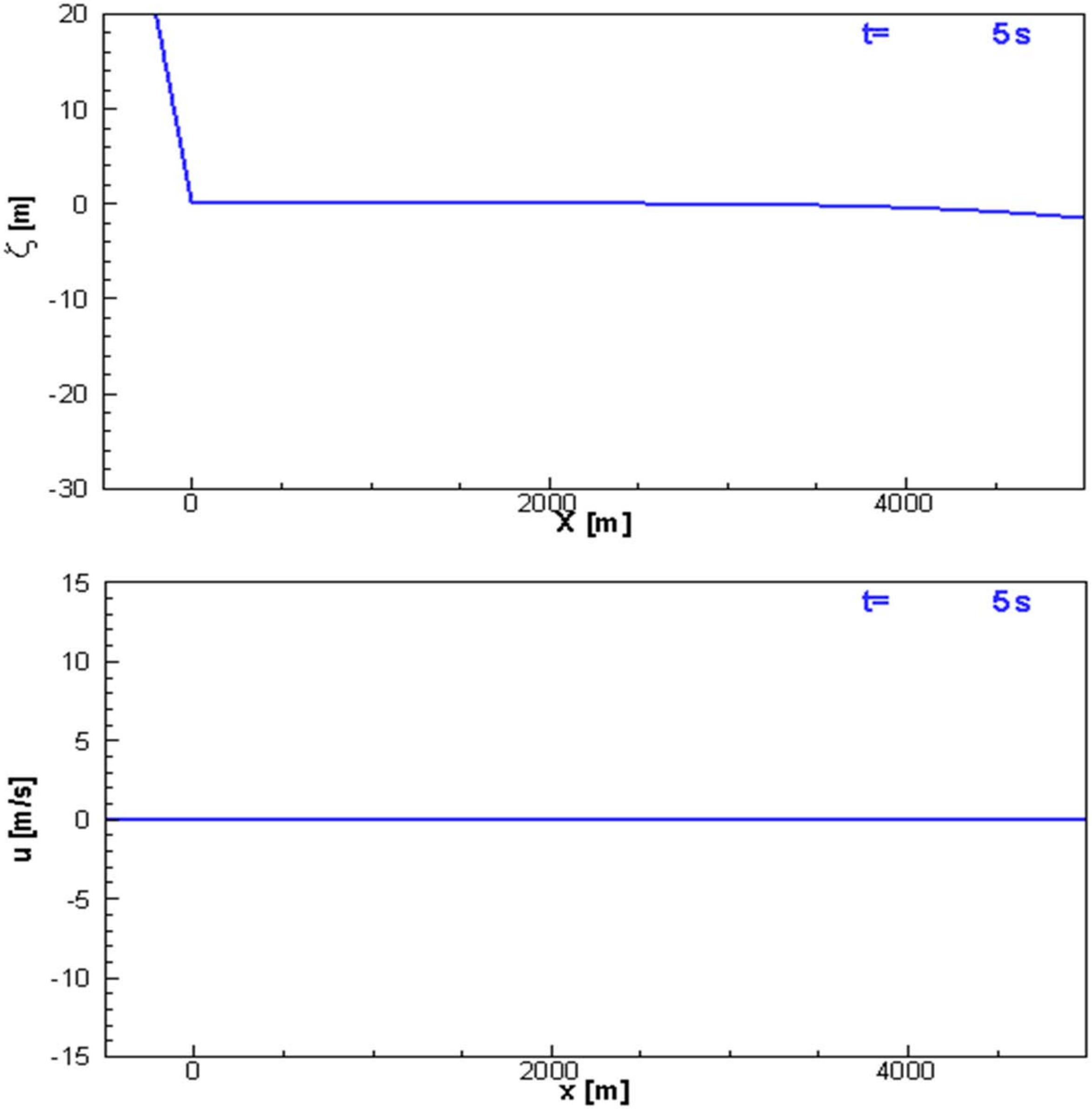
Wet-dry interface:
Linear extrapolation algorithm of Lynett et al. (2002).

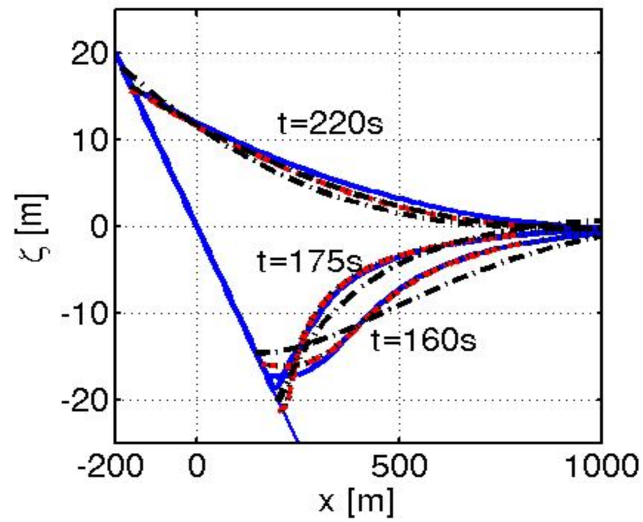
Open boundary, to mimic a damping zone to suppress reflections, (1) expanded the domain with 500 m, and (2)added the condition of Mei & Shyy (1998),

$$f_i(N_d + 1) = 2\, f_i(N_d) - f_i(N_d - 1)\ .$$

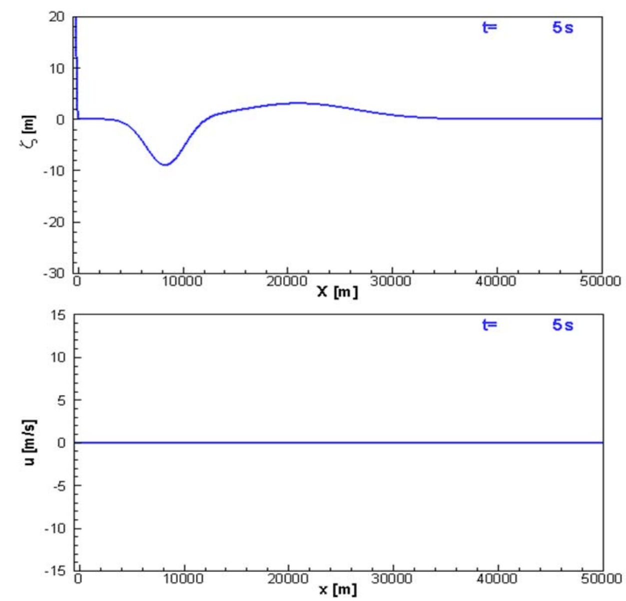
where N_d = 50,500 m.

Near-shore view:



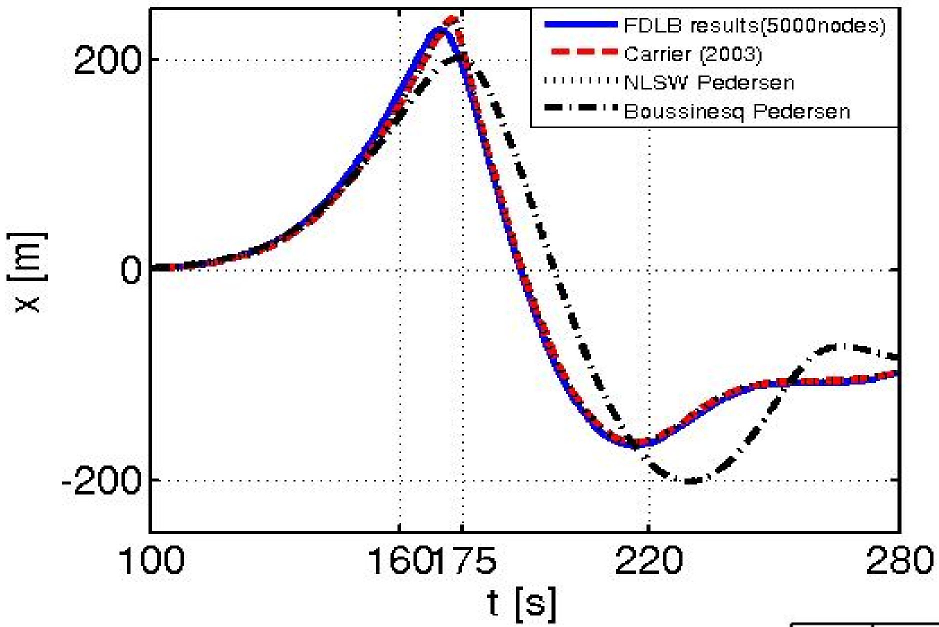


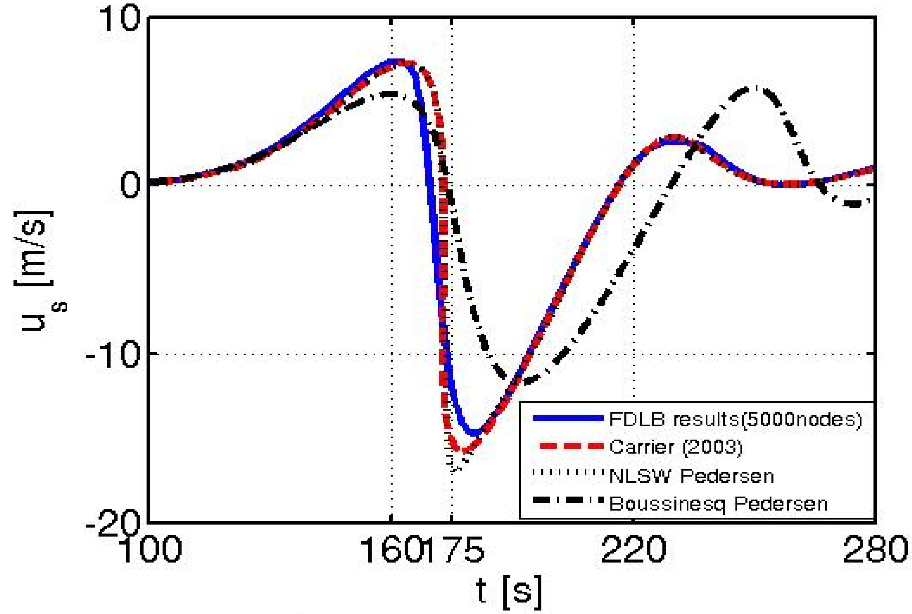
Domain view:

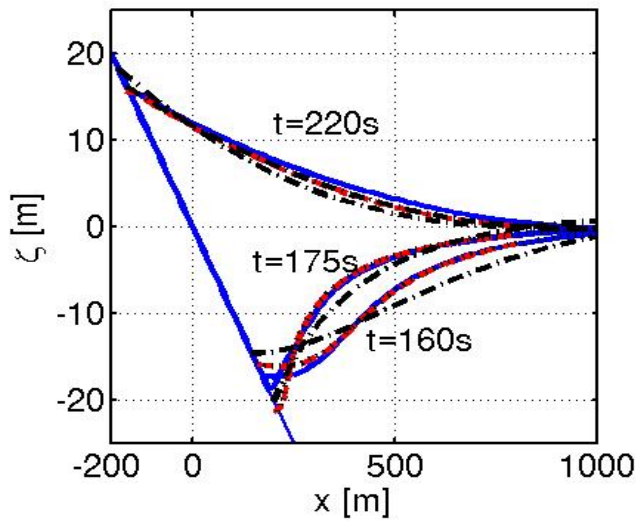


- FDLB model
- 5,000 nodes

Validation

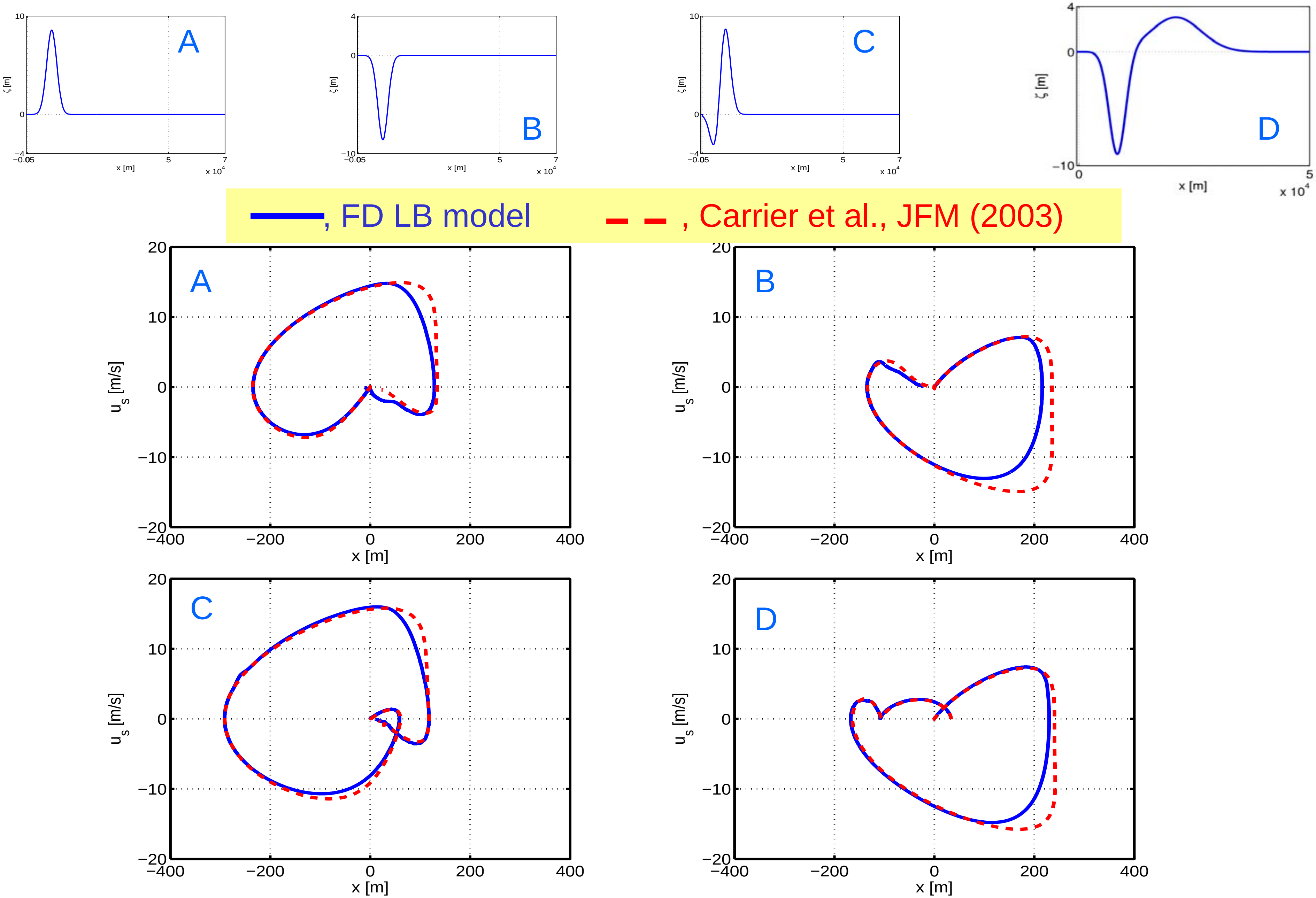






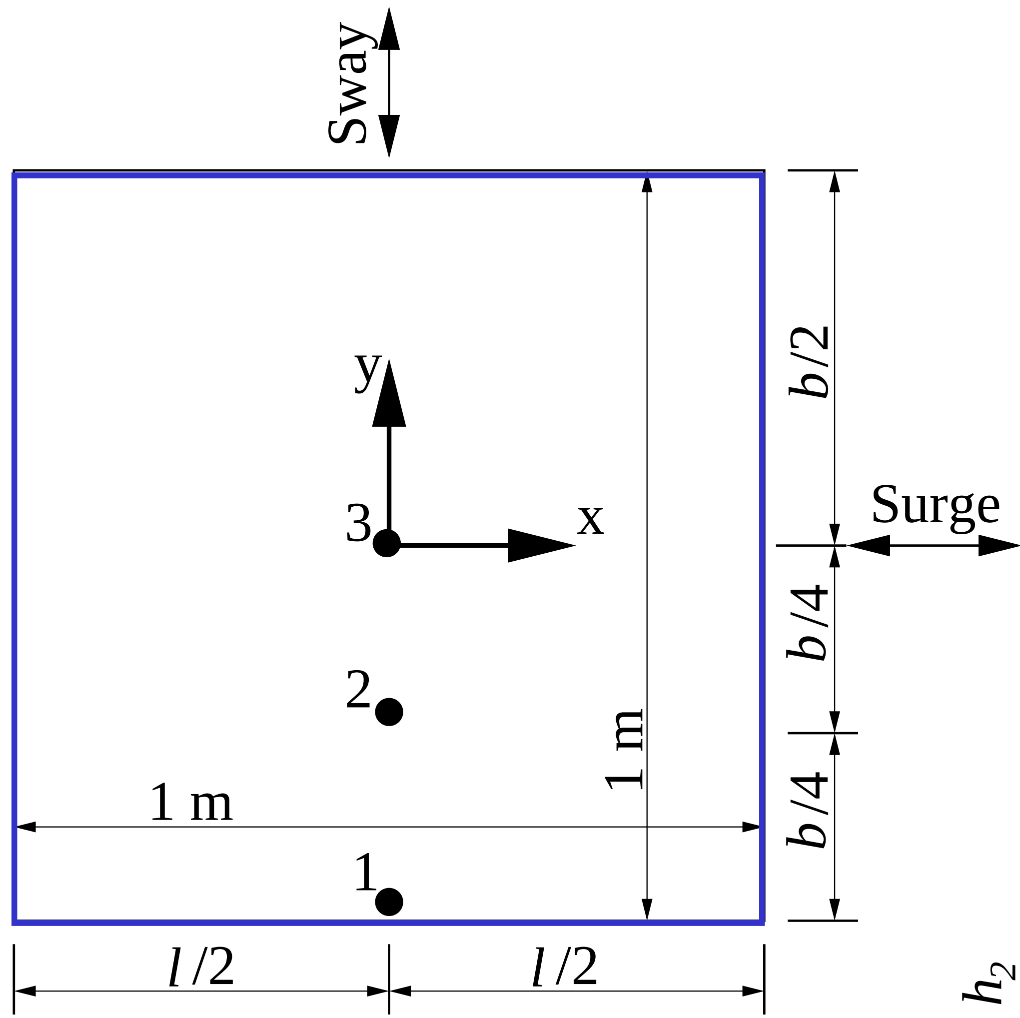
- FDLB model
- 5,000 nodes

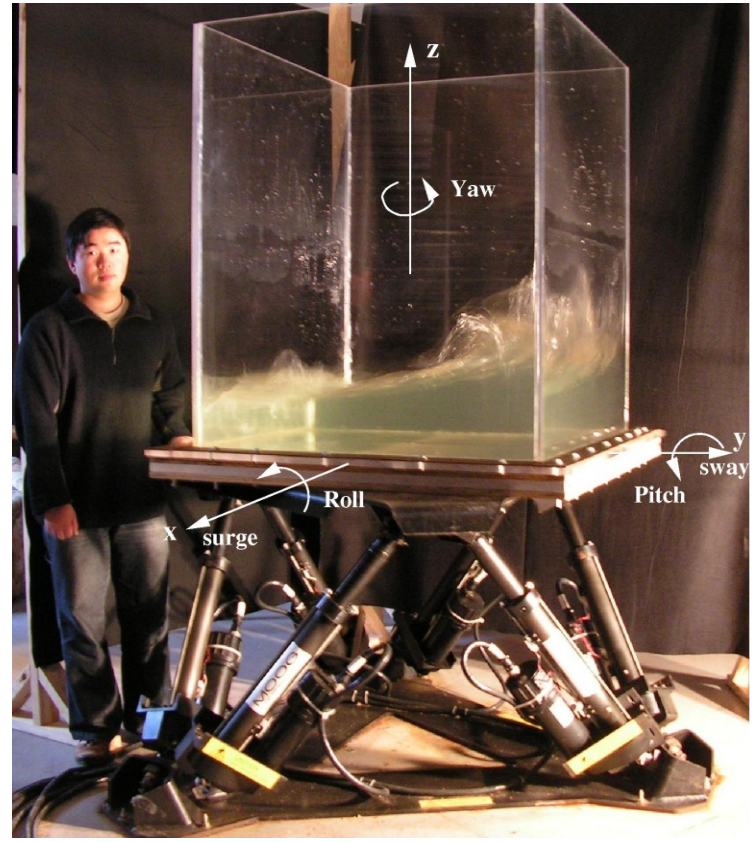
Other initial wave forms

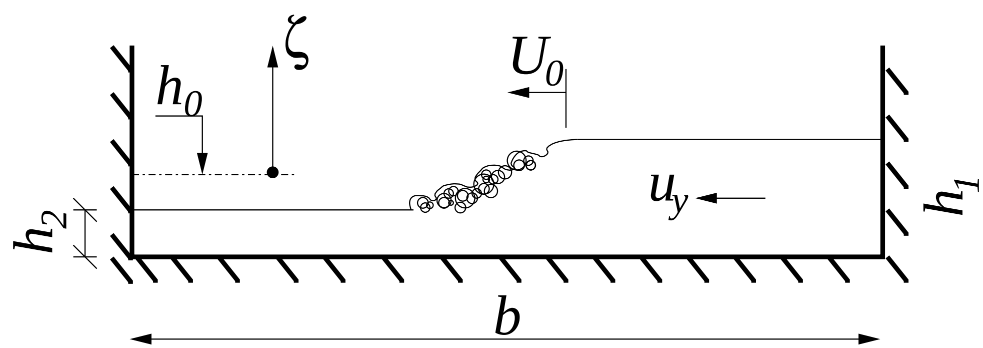


Small Scale Testing

Experimental set-up and definitions



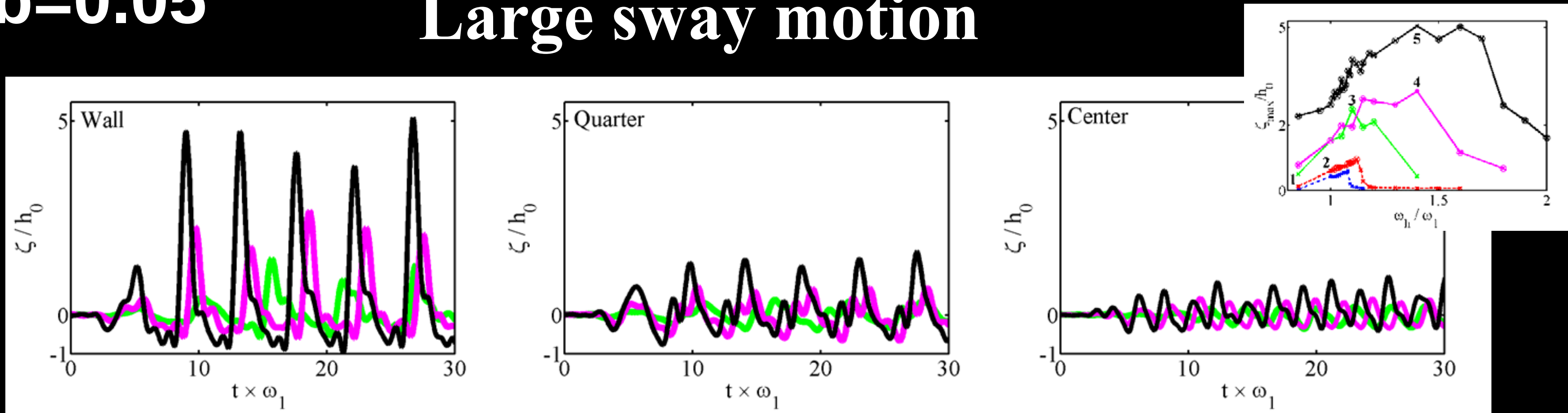


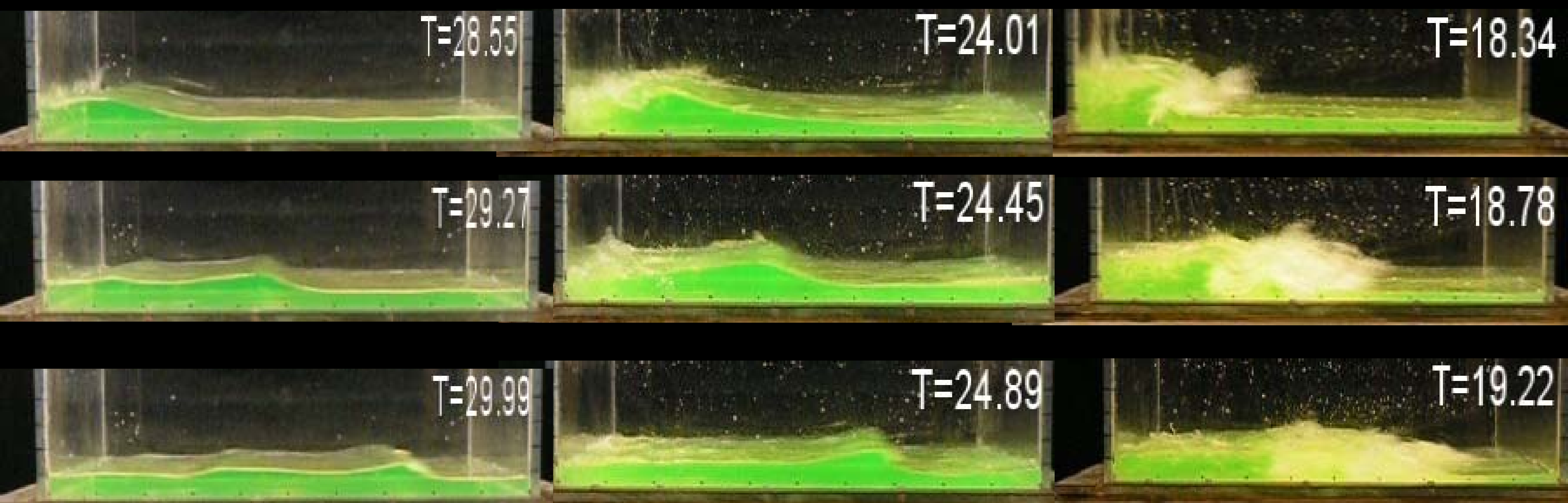


● **Wave gauge**

$h_0/b=0.05$

Large sway motion





$a_h/b=0.02$

$Fr_1=1.1$
$h_1/h_2=1.6$

$a_h/b=0.05$

$Fr_1=1.3$
$h_1/h_2=2.2$

$a_h/b=0.1$

$Fr_1=1.4$
$h_1/h_2=6.9$

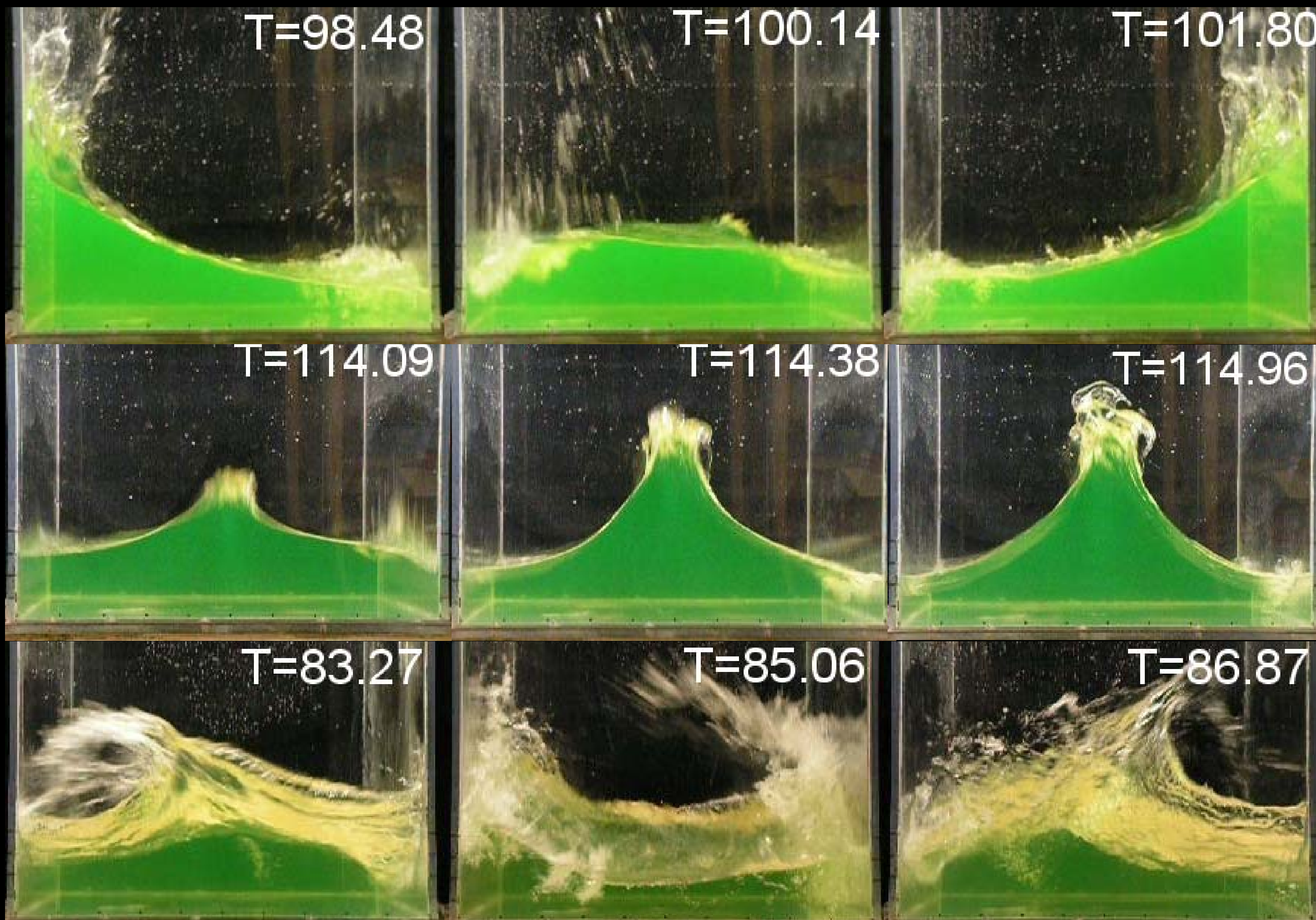
Free-Surface experiments in small tanks

$\underline{h_0/b = 0.2:}$

sway

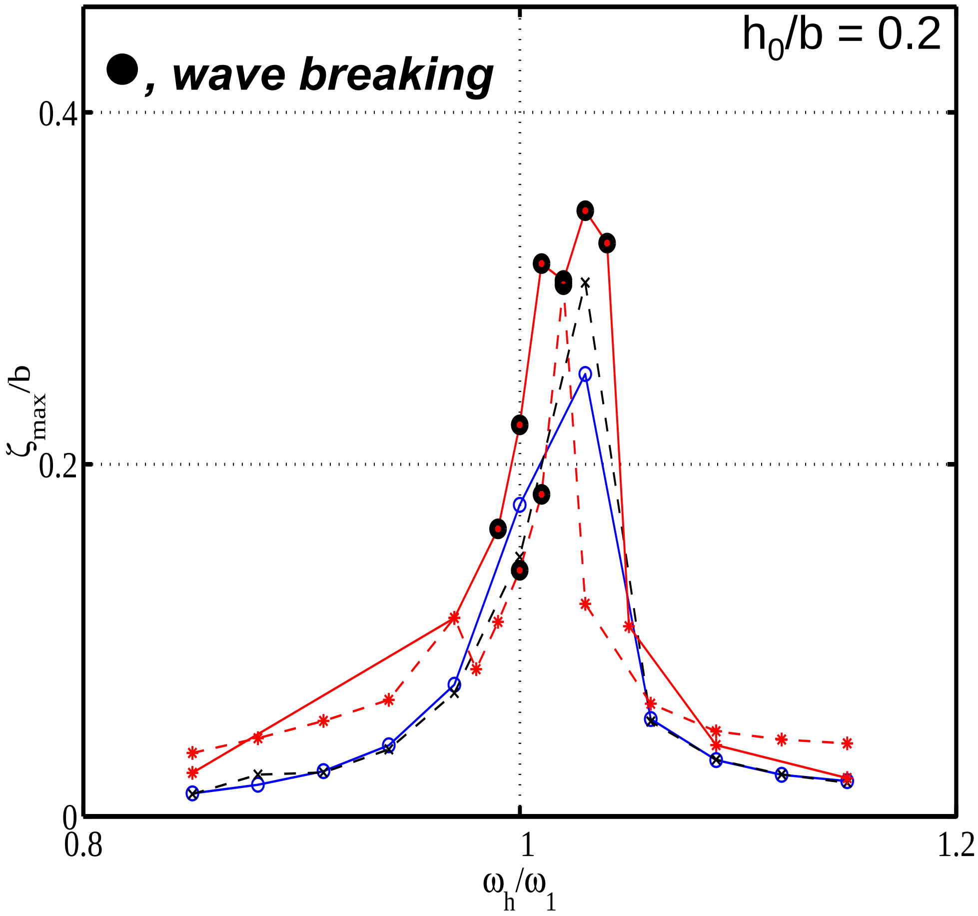
heave

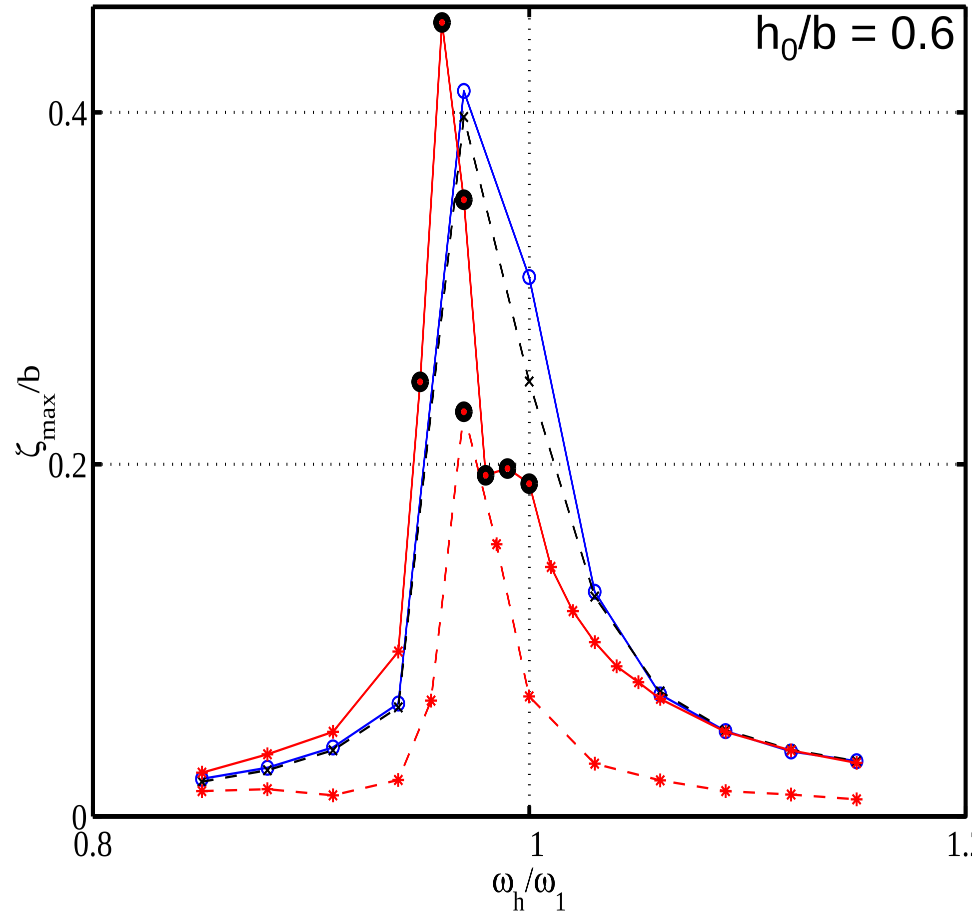
heave
+
sway



Numerical simulations in Frandsen, JCP (2004)

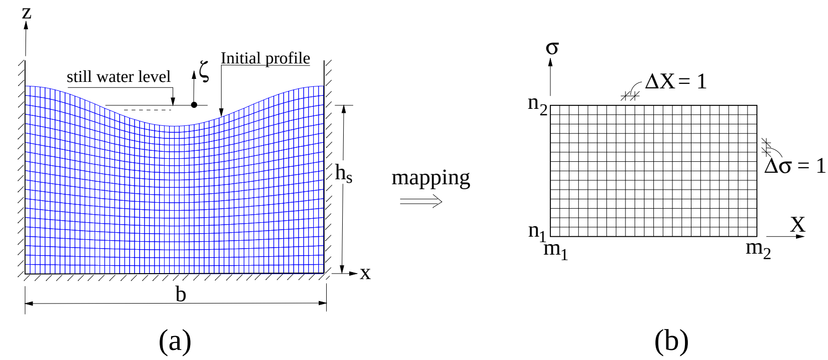
Sloshing in tank: physical vs. numerical test soln





Horizontal moving tank with forcing frequency ω_h

- ***-x -, Analytical 3rd order solution;***
- ***-o-, numerical nonlinear potential flow soln, $a_h/b = 0.003$ (Frandsen, JCP'04);***
- ***- - , experimental solution ($a_h/b = 0.003$);***
- ***—, experimental solution ($a_h/b = 0.006$);.***



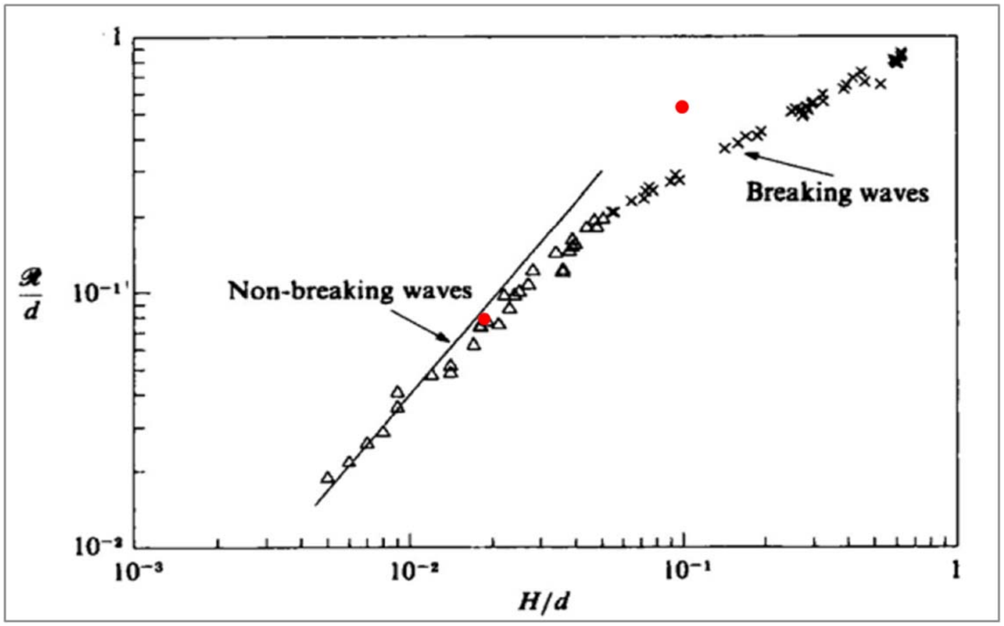
Commercially available

Free-surface VOF LB model

- Free-surface algorithm using Volume of Fluid (VOF) method
  (Ginzburg & Steiner, 2002)
- D3Q27 lattice (recovers the Navier-Stokes equations)
- Mesh: Structured, Octree grids
- Adaptivity: mesh adapts to the wake while the flow develops.
  (constraints on the local dimensionless vorticity.)
- Large Eddy Simulation (local wall adapting eddy viscosity model)
- Multiple Relaxation Time

Wave runup on beaches

Runup height vs. wave height ● LB VOF solns



Wave tank: 37.7 m ⑨ 0.61 m ⑨ 0.39 m

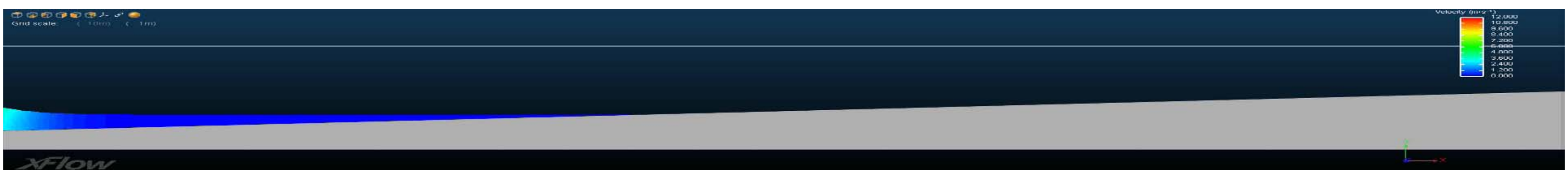
After Synolakis, JFM (1987)

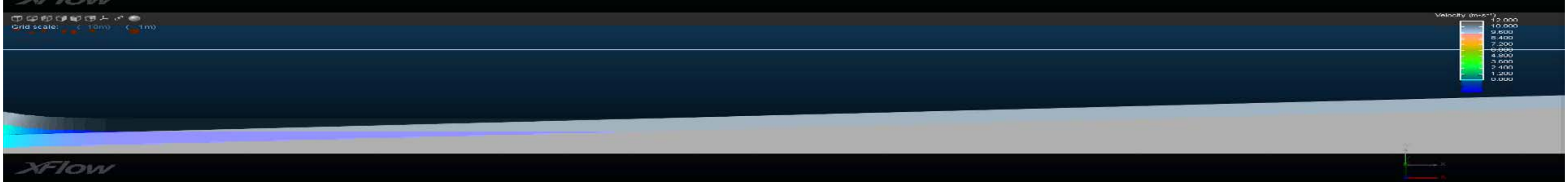
Smooth Beach: 1:19.85

<u>LB solution:</u>

800-900 k elements

H/d =0.5, R/d = 1.511





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Large Scale Testing

- Depth/width: 5 m; Length: 120 m
- Water depth: 2.5 - 3.5 m
- Wave period: 3 - 10 s.
- Wavemaker (piston): max. stroke length/velocity: 4 m, 4 m/s.
- Initial conditions:
  Regular/ irregular waves & user-defined functions,
  e.g., landslide & earthquake-generated tsunami.
- The flume is designed for modeling the interactions of waves, tides, currents, and sediment transport.
- Instrumentation: ADP, ADV, Aquadopp, turbidity-, water level - and pressure sensors. multibeam system (bathymetry).

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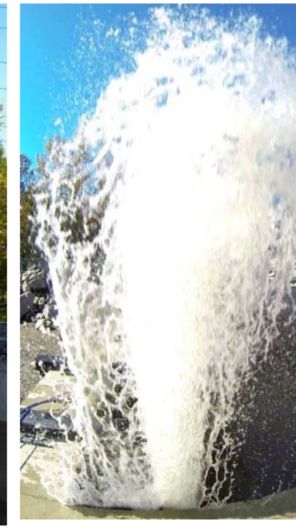
Large Scale Testing

Wave impact on walls



~ 3 – 4 MPa in few ms.

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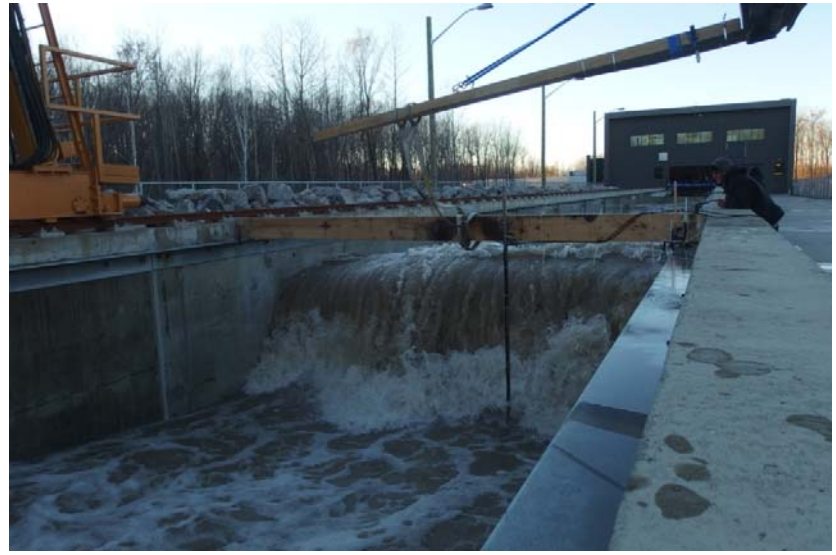
Beach stability experiments

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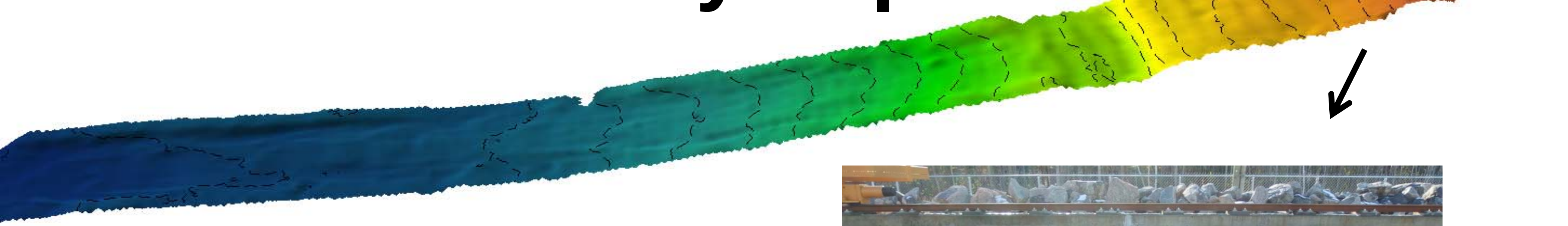
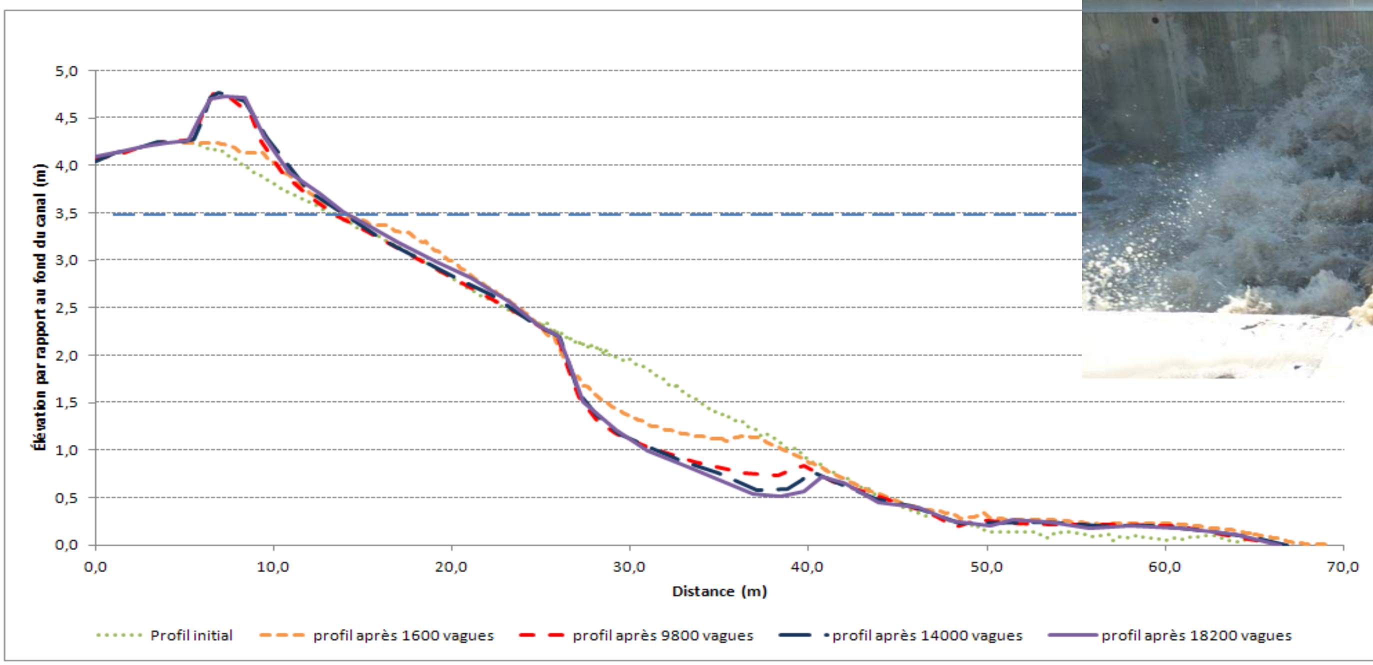
Beach Stability Experiments





Concluding thoughts

Near-shore Hydrodynamic Models

Kinetic approaches when viscosity and complex fluid mixing and structural response as coupled interactions matters.

- **Compatible with other nonlinear shallow water solvers;**
- **Hybrid models to bridge length/time scales;**
- **Assist in design of coastal/harbor structures;**
- **Simplified models in the context of warning systems, evacuation and inundation mapping.**

Questions?